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Monterey, California



THESIS

**RE-OPTIMIZATION OF TIME-PHASED FORCE DEPLOYMENT
PLANS IN RESPONSE TO EMERGENT CHANGES DURING
DEPLOYMENT**

by

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September 1999

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EMERGENT CHANGES DURING DEPLOYMENT**

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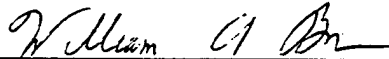
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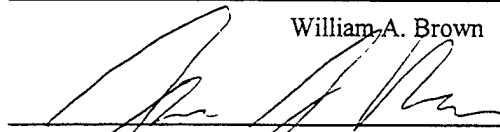
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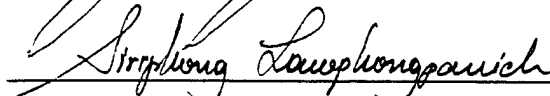


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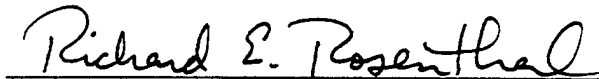
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ABSTRACT

Although Operation Desert Storm has been heralded as a marvel in logistics, it was plagued with inefficiencies. Because of decreases in lift capacity since the Gulf War, and in anticipation of future operations that will likely evolve more rapidly, the U.S. needs better tools to develop efficient logistics plans.

The Warfighting and Logistics Technology Assessment Environment (WLTAE) developed by Johns Hopkins Applied Physics Laboratory simulates the effects of logistical decisions on operational outcomes. WLTAE tracks the flow of units and materiel into ports in theater via a Time Phased Force Deployment Data List (TPFDDL) that remains fixed throughout the simulation, regardless of concurrent port damage. Responding to degradations of ports is an essential feature of robust planning, and requires continuous updates of the TPFDDL.

We show how to modify a TPFDDL and its planned flow of supplies into a theater to account for changes in port capabilities. First, the flows of materiel in the TPFDDL are aggregated into notional ships by a ship-loading heuristic. Second, these notional ships are rescheduled as necessary to alternate ports and/or arrival dates by a ship reassignment heuristic. The solution quality of each heuristic is objectively assessed by comparison with a respective optimal solution to an equivalent mathematical programming model.

DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been tested for all possible cases. While every effort was to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional validation is at the risk of the user.

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LIST OF ACRONYMS AND ABBREVIATIONS

ALD	Available to Load Date
BSR	Berth Ship Ratio
CINC	Commander in Chief
COA	Course of Action
CRD	CINC required Date
EAD	Earliest Arrival Date
ELIST	Enhanced Logistics Intratheater Support Tool
HLA	High Level Architecture
JTOTPFDDL	JOPEs Training Organization TPFDDL
LAD	Latest Arrival Date
LMSR	Large Medium Speed Roll-On, Roll-Off
MTMCTEA	Military Traffic Management Command Transportation Engineering Agency
MRC	Major Regional Conflict
NCA	National Command Authorities
NURR	Non-Unit-Requirement Record
OPLAN	Operations Plan
POL	Petroleum Oil and Lubricants
RORO	Roll-On, Roll-Off
SAH	Ship Assignment Heuristic
SC	SPOD Compatibility
SPOD	Sea Port of Debarkation
SPOE	Sea Port of Embarkation
STON	Short Ton
THUNDER	Air Force operations simulation
TPFDDL	Time-Phased Force Deployment Data List
ULN	Unit Line Number
WLTAE	Warfighting and Logistics Technology and Assessment Environment

EXECUTIVE SUMMARY

The success of Operation Desert Storm has been heralded as a marvel in logistics. Although that logistical effort was tremendous, it was plagued with inefficiencies. The nature of the conflict --- an unopposed 6-month buildup and plentiful United States strategic lift assets at that time --- obscured the need for efficiency. This will not necessarily be the case in future operations that will likely evolve more rapidly. Additionally, the lift capacity of the U.S. military has decreased since the Gulf War and will not increase in the near future. Consequently, the U.S. can no longer afford the logistical luxuries enjoyed in previous conflicts.

A. Background

To enhance planning capabilities, the Warfighting and Logistics Technology Assessment Environment (WLTAE) has been developed at Johns Hopkins University Applied Physics Laboratory. WLTAE links a warfighting simulation (THUNDER) and a logistics simulation (ELIST) in a High Level Architecture compliant environment. WLTAE enables planners to examine the effects of logistical decisions on operational outcomes.

WLTAE tracks the flow of supplies into theater via a Time Phased Force Deployment Data List (TPFDDL). WLTAE views the TPFDDL day-to-day to see what has arrived in each of the Seaports of Debarkation (SPODs). A TPFDDL helps logisticians plan both sea and air transportation to ensure units and materiel are in theater on time. A TPFDDL is developed prior to or during a contingency and contains a list of all the units and supplies that are required by the regional Commander in Chief (CINC) to fulfill the requirements set forth by the National Command Authority. The list contains

records for individual units, e.g. a truck company, and sustainment supplies, e.g. tons of ammunition. The TPFDDL expresses both the Seaport of Debarkation and the arrival time window for each individual record.

Disruptions to the logistical infrastructure can occur throughout the simulation. When a disruption occurs, ELIST, the logistical model within WLTAE, reduces the throughput of the effected port based on the severity of disruption. The TPFDDL, and thus the flow of supplies into SPODs, remain fixed throughout the simulation: there is no rescheduling.

Consequently, the flow of units and supplies into the effected port is diminished and can result in large backlogs if the disruption is severe. No decision making tool is currently available within the simulation that can reroute the units and supplies to alternate ports that are perhaps undisrupted or have excess capacity. Without rerouting, WLTAE does not portray a realistic representation of, say, damage to, capture of, or destruction of a SPOD. Such events are an essential feature of robust planning of theater warfare.

In addition, although the physical movements of units and materiel into SPODs are in shiploads, a TPFDDL is simply a list of things to be transported, and WLTAE does not model merchant ships as objects. Because physical updates of the flow of supplies into SPODs are conducted by rescheduling ship port assignments and arrival dates, the records in a TPFDDL need to be organized into shipload-sized groups.

B. Heuristics Discussion

This thesis presents two heuristics to enhance the realism of the simulation. One is a ship assignment heuristic to build shipload-sized groups of TPFDDL records, and the

other is a ship-to-SPOD reassignment heuristic that reschedules ship destinations and arrival times in response to current capabilities of the SPODs in theater. An equivalent corresponding mathematical optimization model accompanies each of these heuristics. Although optimal answers are desirable, incorporation of optimization software in a simulation suite is not easy, and can significantly increase computational requirements. Nonetheless, the mathematically optimal solutions provide an objective assessment of the quality of plans recommended by the heuristics.

1. Ship Assignment Heuristic

The ship assignment heuristic is a myopic forward-looking heuristic that builds realistic notional discrete ship cargoes by grouping records in the TPFDDL based on their seaport of embarkation (SPOE), their departure window from the SPOE, their SPOD, and their arrival time window into the SPOD. TPFDDL records are also separated by cargo type (e.g. truck company equipment, ammunition or construction supplies, and petroleum). The ship assignment heuristic is tested using a notional TPFDDL and the number of ships loaded is compared with that from an optimal shipload mix. The results suggest that the ship assignment heuristic produces near-optimal solutions in terms of requiring a minimal number of ships.

2. Ship-to-SPOD Reassignment Heuristic

The Ship-to-SPOD Reassignment Heuristic or, more simply, the reassignment heuristic, is a myopic forward-looking heuristic that quickly produces ship-to-SPOD schedules and can be implemented directly in the parent language of a simulation. The incorporation of the heuristic into WLTAE assumes that WLTAE is paused periodically. During each pause, information regarding the SPODs is gathered and, if necessary, some

ships are rerouted to arrive at a different SPOD and on a different date. The goal of the reassignment heuristic is to reroute the ships so as to ensure as many ships as possible are berthed while minimizing disruption to the current overall plan.

A mixed-integer linear program written in the General Algebraic Modeling System (GAMS) assesses the effectiveness of the reassignment heuristic.

Both the reassignment heuristic and the equivalent optimization model have been tested using a notional TPFDDL. Each model is run using a base case with no restrictions on SPOD capacities, and a disruption case that includes a set of SPOD disruptions that alter the original capabilities of the SPODs listed in the notional TPFDDL. The quality of each solution is evaluated with respect to two measures of effectiveness:

- The fraction of ships successfully scheduled to berth during the time horizon and
- The ratio of the number of ships scheduled to arrive at the original TPFDDL SPOD divided by the total number of ships required. This ratio is a simple gauge for adhering to the original theater logistics plan. A high ratio is desirable, and lower ratios indicate SPOD reassignments that necessitate increasing amounts of intra-theater transportation.

The optimization produces a ship-to-SPOD schedule that meets the intent of the original base case TPFDDL. The reassignment heuristic schedules as many ships as the optimization, but the ratio of ships scheduled to arrive at their original TPFDDL SPOD assignment is 15% less. In the disruption case, optimization schedules nearly all of the ships to berth while changing the SPOD assignment only 20% of the time. The reassignment heuristic schedules nearly as many ships to berth as optimization but

changes the SPOD assignment 65% of the time. Optimization solution times can reach 10 minutes on a 200 MHz computer while heuristic solution times are less than 1 second. The reassignment heuristic is fast, but the optimization recommends better schedules.

The reassignment heuristic is adequate for a theater simulation, although not as effective as a formal optimization. Further, this simple heuristic can doubtless be embellished and improved, especially with the reassurance and foundation of an underlying optimization to objectively assess solution quality.

The present heuristic delivers a majority of the notional ship cargoes and consequently a majority of the items in the TPFDDL are available in the required time notwithstanding significant disruptions in many of the SPODs in a theater. Delivering the cargo is the overriding goal of any logistical planner.

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I. INTRODUCTION

The successful buildup and execution of Operations Desert Storm and Desert Shield were heralded as marvels in logistical support. Although the logistical effort was tremendous, it was plagued with inefficiencies. It is estimated that the amount of supplies in theater during the conflict was twice the level that was actually required [Kaminski 1996]. The nature of the conflict that allowed an unopposed 6-month buildup as well as the status of the United States strategic lift assets at that time obscured the need for efficiency. This will not necessarily be the case in future operations, for they will more than likely evolve more rapidly. Additionally, the lift capacity of the U.S. military has decreased since the Gulf War and will not increase in the near future. Consequently, the U.S. can no longer afford the logistical luxuries enjoyed in previous conflicts.

A. BACKGROUND

Recent advances in logistics in the civilian sector brought about by improved information technology as well as a faster and cheaper transportation systems has made the idea of "just in time" logistical chains possible. Contrary to this idea, military organizations have evolved a "just in case" system over the years in response to a cumbersome acquisition system, little or no in-transit asset visibility, and lack of a fast and responsive transportation system [Kaminski 1995].

Dr. Paul Kaminski, then Under Secretary of Defense for Acquisition and Technology, recognized this problem in the mid 1990's and called for the development of modeling tools to enhance the ability of planners and operators to develop and to maintain an efficient support pipeline. This led to the DoD Modeling and Simulation master plan signed by Dr. Kaminski in October, 1995 [DoD 1995].

The principal idea in the master plan is the establishment of a common high-level simulation architecture or HLA to facilitate the interoperability of all types of models and simulations. HLA represents a common framework within which compliant simulation components can be interconnected to build federations of cooperating simulations. The HLA is comprised of three elements defined in three documents [DMSO 1998]:

- i. Interface Specification,
- ii. Object Model Template Specification, and
- iii. HLA Rules for Federates and Federations.

Within an HLA compliant environment, a truly integrated warfighting and logistics simulation is feasible. Prior to HLA, combining these two types of simulations was at best difficult. This is due to the intrinsic differences in the characteristics of the simulations. Warfighting simulations at the theater level generally incorporate aggregated weapons platforms, use small time steps and are stochastic in nature. Logistics simulations generally have higher physical resolution, but use coarse time steps and are deterministic in nature. By linking these two types of simulations together, planners can realistically compare alternate warfighting strategies based on the logistics available in theater. Planners can also analyze the effects of enemy attacks on the logistics pipeline [Sinex, et al 1997]. This allows planners to develop a much more refined logistics plan and to eliminate waste present in previous conflicts.

The Warfighting and Logistics Technology and Assessment Environment (WLTAE) is an HLA compliant simulation currently under development at Johns Hopkins University Applied Physics Laboratory. WLTAE has dynamically linked a Warfighting model (THUNDER) and a logistics model (ELIST) [Sinex, et al 1997].

WLTAE can accommodate a large-scale operation such as a theater-level conflict.

WLTAE updates the overall logistics posture on a day-to-day basis by inputting a stream of units and supplies based on their respective arrival dates as delineated in a Time Phase Force Deployment Data List (TPFDDL).

A TPFDDL is generated prior to the start of the simulation and remains a fixed exogenous entity throughout. As Figure 1-1 shows, a TPFDDL provides the simulation with the information on the arrival port and date for units and supplies.

Disruptions to the logistical infrastructure can occur throughout the simulation. When a disruption occurs, ELIST, the logistical model within WLTAE, reduces the throughput of the effected port based on the severity of the disruption. Because the TPFDDL is fixed, there is no provision to reschedule in response to emergent changes. Consequently, the flow of units and supplies into the effected port is diminished and can result in large backlogs if the disruption is severe. No decision making tool is currently available within the simulation that can reroute the effected units and supplies to alternate ports that are perhaps undisrupted and have excess capacity.

Events during the simulation such as a biological attack at a SPOD necessitate a representation of logistical planning decisions for ship-to-SPOD assignments in response to changes in SPOD capabilities. A change in port availability can drastically change the course of the conflict. With the proliferation of medium-range missiles and chemical and biological weapons of mass destruction around the world, SPOD disruptions are to be expected and need to be accounted for in simulations. Currently, no automated means exists to update the TPFDDL, whether in concert with the conduct of a simulation like WLTAE, or more generally to respond to emergent changes during deployment.

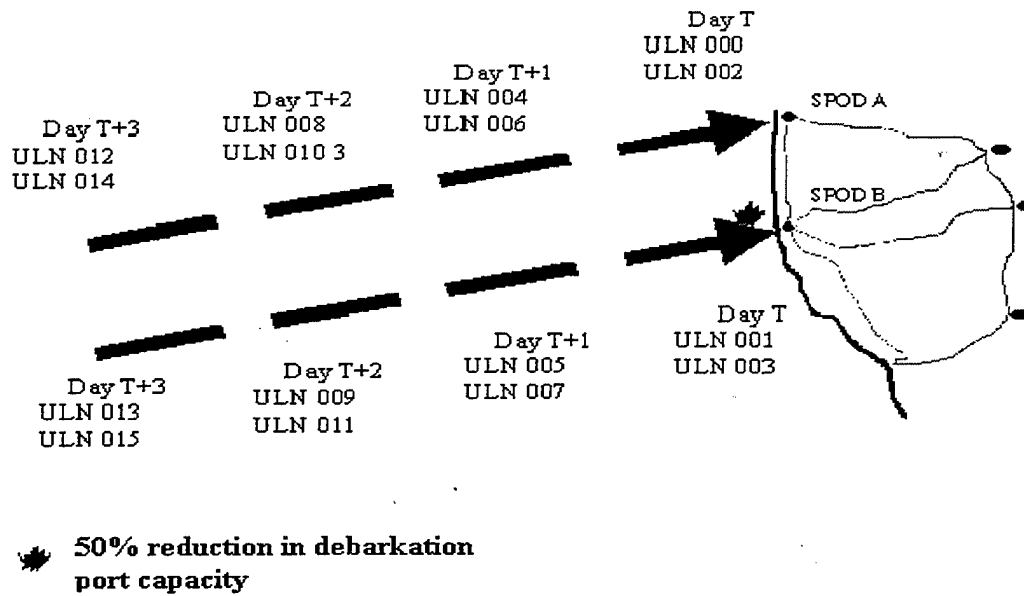


Figure 1-1 TPFDDL Discussion

Expressed via a TPFDDL, supplies and units are viewed as entering the theater of a simulation like WLTAE via a stream of unit line numbers (ULNs) and non-unit related records (NURR) that arrive in a seaport of debarkation (SPOD) based on their respective earliest arrival date (EAD) and latest arrival date (LAD). In the example above, ULNs 000 and 002 arrive in port A and ULNs 001 and 003 arrive in port B on day T. ULNs 004 and 006 will arrive in port A and ULNs 005 and 007 will arrive in port B the following day. The simulation then distributes each unit to its appropriate destination in theater. The static, pre-planned TPFDDL may no longer be the best option if the capacity of the ports is changed or the ports are eliminated or conquered by enemy forces. In this example, on day T of the simulation, a biological attack on SPOD B has decreased its capacity by 50%. A new logistical plan is required to reroute ULNs scheduled to arrive subsequent to such a change in a manner that minimizes the deviation from the regional Commander in Chief's (CINC's) required dates. An optimization program can assign new port designations for each ULN based on the new capacity of the ports remaining as well as the capacity of the land transportation network that funnels the units and supplies to their respective destinations to the east.

B. PROBLEM STATEMENT

Currently, the TPFDDL is developed prior to running the WLTAE simulation and remains unchanged during an entire run, regardless of the evolving status of the forces in theater or the Seaports of Debarkation (SPODs). This does not provide a realistic depiction of how joint staff logistics planners would operate in combat. The ideas

proposed in this thesis would enhance the logistical aspect of WLTAE by automatically updating the TPFDDL on a day-to-day basis. More precisely, this thesis proposes a method for redirecting units and supplies already enroute to alternate SPODs and, perhaps, at different arrival dates. Additionally, the methodology proposed herein is sufficiently general, in that it is also applicable to other warfighting models that attempt to combine both logistical and operational aspects of battle.

C. APPROACH

We suggest incorporating logistical planning into WLTAE as follows. First, group records in the TPFDDL into notional shiploads. At the beginning of a simulation run, schedule each shipload to arrive at the SPOD and on the arrival date suggested by the TPFDDL. Second, we assume that the WLTAE simulation can be paused periodically. During each pause, information regarding the SPODs is gathered and, if necessary, some ships are rerouted to arrive at a different SPOD and/or on a different date.

This thesis proposes heuristic methods to respectively group TPFDDL records into shiploads, and to reroute ships. We evaluate the heuristics by comparing their solutions with those of corresponding, equivalent mathematical optimization models --- models probably too difficult to incorporate into a simulation and too expensive to run repeatedly within a simulation, but nonetheless invaluable for objectively assessing the quality of heuristic solutions.

D. THESIS OUTLINE

Chapter II describes the development and content of a TPFDDL, and also describes a heuristic that groups TPFDDL records into notional shiploads. This heuristic is evaluated with respect to an equivalent optimization model. Chapter III presents a heuristic to reschedule ships to SPODs. This heuristic is also evaluated with respect to an equivalent optimization model. Chapter IV concludes the thesis and offers recommendations for further studies.

II. TPFDDL DISCUSSION AND NOTIONAL SHIP DEVELOPMENT

A. TPFDDL DEVELOPMENT AND DESCRIPTION

When a crisis erupts anywhere in the world, the National Command Authorities (NCA), an organization composed of the President, Secretary of Defense, and Secretary of State, assesses the diplomatic, economic, and information implications and decides whether military action is justified. If the NCA chooses a military response, the CINC responsible for the region in question develops, in conjunction with the Chairman of the Joint Chiefs, several courses of action (COA) in response to the situation. The NCA selects a COA and the CINC issues the corresponding Operations Plan (OPLAN) [AFSC Pub 1 1997].

An OPLAN is "any plan for the conduct of military operations. Plans are prepared by combatant commanders in response to requirements established by the Chairman of the Joint Chiefs of Staff and by commanders of subordinate commands in response to requirements tasked by the establishing unified commander" [Joint Pub 1-02 1999]. It includes a list of all the major forces required as well as the logistical administrative plans needed to support the operation [AFSC Pub 1 1997].

Each OPLAN contains a TPFDDL to support the operation. The TPFDDL "describes, routes, and aggregates cargo movement characteristics of forces defined for the OPLAN as well as the non-unit sustainment, i.e., supplies and cargo" [AFSC PUB p.6-81, 1997]. A TPFDDL is not a fixed entity. It is revised continuously throughout the campaign in response to unplanned events.

In a TPFDDL, a major unit such as an Army division is broken down into its component units, i.e., battalions, companies, etc. Each of these component units has its

For any operations longer than 15-30 days (the duration of supply generally included with a unit's organic assets), follow-on sustainment supplies are required. The TPFDDL includes all of these exogenous sustainment supplies including fuel, ammunition and medical supplies in addition to ULNs. These exogenous cargo items are called non-unit-requirement records (NURRs). For a large operation such as a Major Regional Conflict (MRC), these NURRs compose the majority of the records in the TPFDDL.

The NURRs do not correspond to individual shipments of items like ULNs. Rather, they denote the amount of each class of sustainment supplies required at each SPOD by a particular day. For example, the record shown in Figure 2-3 requires 1200 Short Tons (STONs) of ammunition be available at SPOD FMBC by day C+58.

<u>GAR02165RRHU36RRHU36C047</u>		XG		<u>FMBCSAC048C058</u>		SE
<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>	<u>E</u>	<u>F</u>	<u>G</u>
JWJSSAC060LD		MDBA5	00000000001200000009000000			
		<u>H</u>	<u>I</u>	<u>J</u>		
Munitions	0					

Figure 2-3 TPFDDL Description (NURRs)

An example of a non-unit-related record, a NURR, taken from a TPFDDL. The underlined sections are pertinent data fields utilized in this thesis. Field A designates the record as a non-unit-related record. Field B is the sequencing number, like an identifier. Field C is the SPOE. Field D is the ALD. Field E is the SPOD. Field F is the arrival window the supply is required at that SPOD. Field G is the mode of transportation. Field H is the cargo class (e.g., 5 refers to ammunition). Field I is the cargo weight (in short tons). Field J is the amount of Cargo Bulk Petroleum Oil and Lubricants (POL) (in hundreds of barrels).

The data fields in a TPFDDL assist logisticians in developing plans to assign both sea and air transportation assets as required to ensure units are in theater on time.

However, the TPFDDL does not specify how the cargo will be loaded into ships or aircraft for transport into theater.

Additionally, WLTAE does not model merchant ships as objects. Rather, it looks at the TPFDDL on a day-to-day basis in order to determine whether ULNs and NURRs have arrived at each of the SPODs. After their arrival at SPODs, the simulation assigns truck and cargo aircraft objects for intra-theater distribution of the materiel and units.

To more realistically represent the TPFDDL during the simulation, the units and supplies need to be placed into discrete ships that can be redirected as required. Since a TPFDDL is a list of items to be transported from one location to another and WLTAE does not model cargo ships, notional ships are necessary and ship objects need to be developed and incorporated into WLTAE. Once created, these notional ships are then loaded with ULNs and NURRs listed in a TPFDDL via a Ship Assignment Heuristic (SAH) developed below.

B. NOTIONAL SHIP DESCRIPTION

In this thesis, the notional ships are designed to reflect the types of ships currently utilized to transport U.S. forces and sustainment supplies during conflicts. Although there are many types and classes of merchant ships, three general ship classes are used here as notional ships (see Table 2-1). The size of the roll on, roll off (RORO) ships is based on the average of the new Large Medium Speed Roll/ON Roll/OFF (LMSR) and the older RORO ships used in the Gulf war that are still in the U.S. inventory. The size of the container and POL ships are based on the typical ship used during the Gulf War [Matthews 1992].

Ship Type	Size (in STONS)	Cargo Description
Roll-On Roll-Off (RORO)	8500	ULNs
Container	7000	NURRs composed of "dry cargo" such as ammunition, food rations etc.
POL (tankers)	10000	NURRs composed of POL items

Table 2-1 Ship Objects

Characteristics of the various notional ship objects.

C. SHIP ASSIGNMENT HEURISTIC

SAH is implemented in Java™.¹ SAH creates objects representing ships. The attributes associated with these objects are from the TPFDDL and they include:

- Record Vector: a list of all the ULNs or NURRs loaded on the Ship object,
- SPOD,
- EADLAD: the arrival window at the SPOD of the Ship object,
- SPOE,
- ALD: the departure date from the SPOE of the Ship object,
- Weight: the total weight (in STONS) of all of ULNs or NURRs loaded on that ship object,
- Supply Class: the cargo type each Ship object contains. Each Ship object can only carry one type of cargo, either ULN, NURR dry cargo, or NURR POL cargo, and
- Size: certain ULNs are larger than the average size RORO. Instead of arbitrarily splitting a large ULN between different Ship objects, these ULNs are assigned their own Ship object.

¹ Java is a trademark of Sun Microsystems Computer Corporation.

For each ULN and NURR, SAH creates a Record object with attributes from the Ship object as well as the following:

- CRD: the date that the ULN must arrive and unload at its destination,
- Type: the type of record, either ULN or NURR,
- Assembly area: the location where all ULNs in the same force module need to come together prior to the CRD. A force module contains all of the elements of a combat unit, and
- Transportation mode: the transportation mode for the Record object, either air or sea.

To organize thousands of records in the TPFDDL into notional ships, SAH examines each record once and assigns it to an appropriate notional ship based on its departure and arrival dates (ALD and EAD/LAD data fields) and its respective SPOE and SPOD. Since a ULN is different from a NURR, SAH deals with each of these record types separately.

For each TPFDDL record, SAH determines its type and executes the appropriate commands necessary to assign it to a particular ship object. The program tracks the Ship objects through the use of two vectors. The first, called the unit ship vector, is a list of all unit Ship objects that transport ULNs. The second vector, called the sustainment ship vector, tracks all sustainment Ship objects that transport NURRs.

The method for assigning TPFDDL records to notional ships follows:

1. Create a Record object for a ULN and NURR in the TPFDDL, extracting all necessary attributes from the appropriate data fields,
2. If the Record object requires air transportation, discard the object and return to 1, otherwise, go to 3,

3. Determine whether the Record Object is a ULN or NURR. If the Record Object is a ULN use the Unit Ship Method otherwise, use the Sustainment Ship Method, (Both methods are described below.)
4. If there are no more TPFDDL records, stop. Otherwise, go to 1.

1. Unit Ship Method

SAH assumes that all ULNs on the same ship must leave and arrive at the same ports on exactly the same set of departure and arrival dates. The method for assigning ULNs to unit Ship objects follows:

1. Compare the SPOE, ALD, SPOD and EADLAD of the Record object with each Ship object in the unit ship vector,
2. If a match is found, the total weight of the unit Ship object including the weight of all previously assigned Record objects and the Record object in question is calculated,
3. If the total weight does not exceed the maximum weight of the unit Ship object, assign the Record object to that Ship object and adjust the ship's weight to reflect the addition of a new ULN,
4. If the total weight exceeds the maximum weight of the unit Ship object, continue to look for a Ship object with similar attributes whose weight is not exceeded with the addition of the Record object,
5. If a match is not discovered or the additional weight of the Record object exceeds the maximum weight of all unit Ship objects with similar attributes, a new unit Ship object is created that matches the attributes of the ULN. Assign

the Record object to that ship object and adjust the ship's weight to reflect the addition of a new ULN, and

6. Add the new unit Ship object to the unit ship vector.

2. Sustainment Ship Method

NURRs are given a supply class, e.g., ammunition, sustenance, or petroleum.

Because petroleum is generally only transported via tankers and all other supplies (dry supplies) via break-bulk or container ships, a further distinction between ships is necessary. Consequently, only Ship objects that already have petroleum products loaded can accept subsequent petroleum type Record objects and likewise container ship objects can only load dry supply NURRs.

Because each NURR represents a discrete parcel of a continuous flow of supplies into the theater rather than a discrete unit like a ULN (see Figure 2-4), a different process is necessary to assign NURR records to sustainment ship objects.

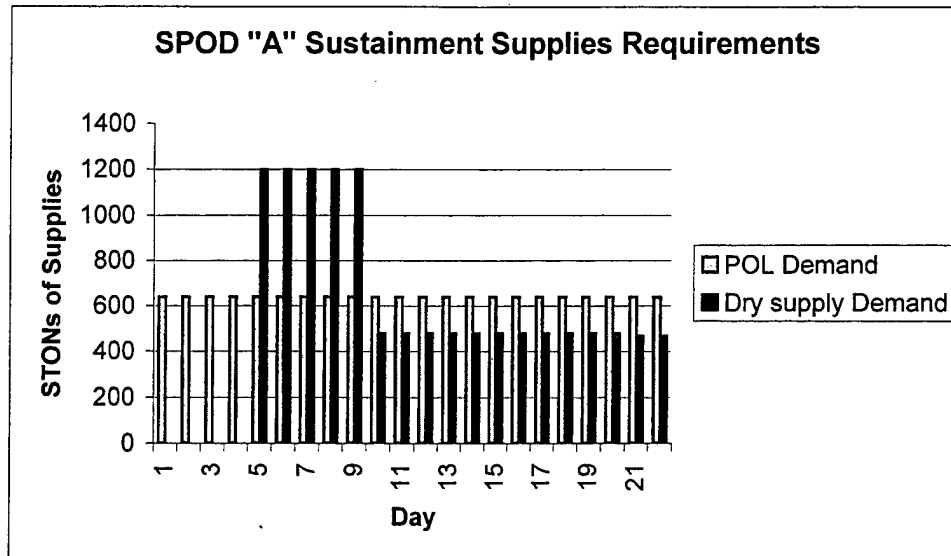


Figure 2-4 Sustainment Supply Example

Starting on day 1, a constant rate of petroleum demand must be satisfied through day 25 as well as a varying rate demand for dry supplies beginning on day 5 and demanded through day 25. A NURR is created for each day that a particular class of sustainment supply is required, e.g. in the TPFDDL, a NURR is listed requiring 5000 STONs of POL at SPOD A on day 5 as well as another NURR requiring 1200 STONs of ammunition at SPOD A on day 5.

The NURR method follows:

1. Compare the SPOD and materiel type of the NURR with each Ship object in the sustainment ship vector.
2. If a Ship object with the same materiel type is scheduled to arrive at the SPOD prior to the Record Object's EAD, the total weight of the unit Ship object including the weight of all previously assigned Record objects and the Record object in question is calculated,
3. If the total weight does not exceed the capacity of the Ship object, the Record object is assigned and the total weight of the Ship object adjusted to reflect the additional Record object, and

4. If the total weight exceeds the capacity of the Ship object or no sustainment Ship object with the same materiel type arrives at the SPOD prior to the Record Object's EAD, create a sustainment Ship object that arrives on the day corresponding to the NURR's EAD and its type of supply (either petroleum or dry).

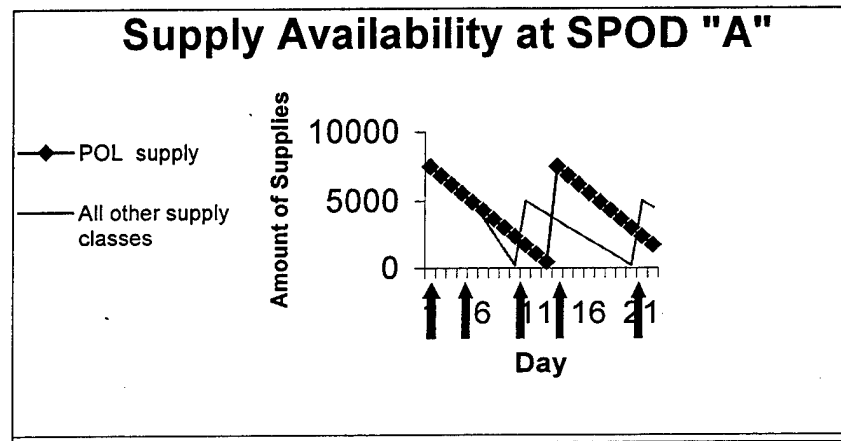


Figure 2-5 Sustainment Ship Example

SAH schedules a petroleum-type sustainment ship object to arrive on days 1 and 13 and a dry supply-type sustainment ship object to arrive on days 5, 10, and 21 in order to satisfy SPOD sustainment supply demands. The black arrows indicate ship object arrivals.

Figure 2-5 provides an example for assigning the NURRs represented in Figure 2-4 to notional ships. On day 1, a NURR requires 640 STONs of POL to arrive at SPOD A. SAH creates a POL sustainment Ship object with an arrival date of day 1 of materiel type POL, containing 640 STONs of POL. The next NURR demands an additional 640 STONs of POL to arrive at SPOD A on day 2. SAH assigns the NURR to the previously describe Ship object and adjusts it weight to 1280 STONs of POL. This procedure is repeated until the NURR is encountered that requires 640 STONs of POL to arrive on day 13. SAH calculates that the addition of the NURR exceeds the Ship Object's maximum weight and therefore schedules a new Ship object to arrive at SPOD A on day

13 with 640 STONs of POL. This procedure is continued for the remainder of the NURRs listed in the TPFDDL.

D. SAH RESULTS

SAH tries to induce from the TPFDDL an implicit underlying shipping plan, and tries to do so with a minimal number of notional ships that are as full as possible. During the Gulf War, ships were loaded in a manner that maximized the amount of cargo on each vessel in order to reduce the number of merchant ships required to support the TPFDDL. To objectively assess the quality of the SAH heuristic, we employ an equivalent optimization model.

1. An Optimization Model to Minimize the Number of Notional ULN Ships

The following mixed-integer program minimizes the total number of ships required to transport all the ULNs in a TPFDDL. To reduce computational requirements, and with no loss of generality, the ULNs in a TPFDDL are broken down into disjoint sets of similar SPOE departure windows ($depwin_c$). The monolithic model is solved by successively minimizing the number of notional ships required to transport all of the ULNs in each SPOE departure window set.

a. Indices

$s \in S$	ship {notional ships described in Section B}
$c \in C$	cargo {TPFDDL record, e.g., ULN001}
d, dd	SPOE departure window {depart SPOE 0 on ALD 003}
$depwin_c$	SPOE departure window for cargo c

b. Data

$weight_c$	weight of cargo c (stons)
------------	-----------------------------

c. Variables

$ASSIGN_{s,c}$ =1 if ship s is assigned cargo c
 =0 otherwise
 $DEPART_s$ =1 if ship s is used

d. Formulation

$$\text{Min } \sum_s DEPART_s \quad \{1\}$$

Subject to:

$$\sum_{c|depwin_c=dd} ASSIGN_{s,c} \times weight_c \leq 8.5 \quad \forall s \quad \{2\}$$

$$ASSIGN_{s,c} \leq DEPART_s \quad \forall s, c | depwin_c = dd \quad \{3\}$$

$$\sum_s ASSIGN_{s,c} = 1 \quad \forall c | depwin_c = dd \quad \{4\}$$

$$DEPART_s, ASSIGN_{s,c} \in \{0,1\} \quad \forall s, c \quad \{5\}$$

2. Verbal Formulation

The objective function (1) minimizes the total number of notional ships required.

Constraints:

- (2) Constraints ensure that the capacity (e.g. 8500 stons) of each notional ship is not exceeded.
- (3) Constraints ensure that if a ship carries cargo that ship is counted in the objective function.
- (4) Constraints ensure that each cargo is assigned to exactly one ship.
- (5) Binary decisions are required.

3. Comparison with Heuristic SAH

The heuristic SAH results are compared with those of the optimization. Both programs were tested using a TPFDDL involving a Persian Gulf scenario downloaded from the JOPES Training Organization [JOPES Training Organization 1998] referred to herein as JTOTPFDDL. The optimization model is implemented in Generic Algebraic Modeling System (GAMSTTM) and solved by the XA solver [Brook et al 1997] on a 200 MHz processor. Table 2-2 shows the size and solution effort for the 67 disjoint SPOE/ALD departure window subproblems in the JTOTPFDDL test case.

	Variables		Number of Equations	Solution Times (seconds)
	Discrete	Cont.		
Average	76.6	77.6	95.58	16.21
Maximum	544	545	680	377.7
Minimum	4	5	1	0

Table 2-2 Computational Requirements (ULN Ship Assignment Opt. Model)

Computational Requirements for the ULN Ship Assignment optimization model over the 67 different model runs necessary for the complete set of ULNs in a notional TPFDDL.

Table 2-3 compares the number of ships required for each method.

Method	Number of Ships Required	CPU Time (seconds)
SAH	110	59.8
Optimal Solution	109	1085.9

Table 2-3 SAH Results (all ULNs)

Comparison of the number of ships required by the heuristic SAH and a mathematically optimal cargo mix using the minimum number of ships for all ULNs in TPFDDL.

To further analyze SAH, 10 random subsets are sampled from JTOTPFDDL producing 10 different TPFDDL examples. Table 2-4 compares the number of ships required for each method. The results suggest that SAH is an effective method for assigning ULNs and NURRS to ships.

Sample	Number of Ships Required				% of Optimal Solution
	Optimal	CPU Time	Heuristic	CPU Time	
1	45	3.52	46	1.28	97.8
2	45	3.74	45	0.86	100
3	45	3.68	45	2.89	100
4	42	4.00	42	1.12	100
5	46	4.06	46	1.34	100
6	48	3.96	48	1.47	100
7	47	4.34	47	1.80	100
8	50	3.62	50	1.87	100
9	48	3.62	48	1.01	100
10	43	3.52	43	1.23	100
Average % of Optimal					99.8

Table 2-4 SAH Results (samples from TPFDDL)

Comparison of the number of ships required by the heuristic SAH and a mathematically optimal cargo mix using the minimum number of ships for random samples of ULNs in TPFDDL.

III. SHIP-TO-SPOD REASSIGNMENT HEURISTIC

Periodically, say daily, during the warfighting scenario, WLTAE can be paused. Specified data including SPOD capabilities that could have been altered by events over the previous day can be then extracted for analytical purposes. A heuristic, implemented in the parent language of the simulation, can then reschedule ship-to-SPOD assignments based on current SPOD capabilities.

A. SHIP-TO-SPOD REASSIGNMENT HEURISTIC DESCRIPTION

The Ship-to-SPOD Reassignment Heuristic or, more simply, the reassignment heuristic, is a myopic forward-looking heuristic that quickly produces ship-to-SPOD schedules and can be implemented directly in the parent language of a simulation. It requires SPOD capability information that is readily available in WLTAE. It attempts to berth each ship at the original SPOD during the ship's arrival window prior to examining any other candidate SPODs. The goal of the reassignment heuristic is to ensure as many ships as possible are berthed while minimizing deviation from the original SPOD. The method follows:

1. Assess the status of each SPOD capability area, the berths available, and the amount cargo already stored. Develop an array of all of the ships required by the TPFDDL and arrange them in order of arrival into theater.
2. Attempt to berth each ship at its SPOD by the ship's EAD or the date of the simulation, whichever is later. If berths are available, schedule the ship to berth at that SPOD on that date. Update the number of berths available, cargo stored, and cargo transported away for the receiving SPOD for that arrival date and every subsequent day required to unload the ship based on the SPOD's offloadrate.

3. If there are no berths available, try each subsequent date until an available berth is located or the date exceeds the ship's LAD for that SPOD.
4. If no berth is located at the original SPOD, try the next geographically closest SPOD to the original SPOD and repeat the process.

B. REASSIGNMENT HEURISTIC RESULTS

The quality of the reassignment heuristic is evaluated with two measures of effectiveness:

- SPOD Compatibility (SC): the ratio of the number of ships scheduled to berth at their original TPFDDL SPOD assignments to the total number of ships required. Solutions that schedule more ships at their original TPFDDL SPODs are considered better because the assembly area for each force module is generally near a particular SPOD designated for its component ULNs or NURRs in the TPFDDL. Reducing the number of SPOD changes reduces the amount of intra-theater transport required by the revised schedule.
- Berthed Ship Ratio (BSR): the fraction of ships scheduled to berth during the time horizon. The overriding goal of the model is to ensure the maximum number of ships is berthed during the course of the simulation and consequently the maximum amount of cargo is available to the CINC in a timely manner.

The reassignment heuristic is implemented in Java™ but can be implemented in any general-purpose programming language utilized by the simulation. Compilation and computation time for the JTOTPFDDL scenario is less than 1 second.

To examine the effects of disruptive events in a warfighting simulation, the reassignment heuristic is tested using a base case with nominal SPOD capacity and a case

with SPOD throughput disruptions. For the base case, the reassignment heuristic is tested using inputs from JTOTPFDDL. The capabilities for each of the SPODs are fixed throughout the 100-day planning horizon designated in the TPFDDL and consistent with the data listed in Table 3-1. Table 3-2 compares the results from the model against the requirements delineated in the original TPFDDL. The reassignment heuristic schedules 99% of the ships to berth while scheduling the ships to arrive in the same SPOD as in the TPFDDL 85% of the time.

		SPOD Capability Areas					
		Offload Rate (STONS/day)		Storage Capacity (STONS)		Road/Rail Capacity (STONS)	
SPOD	Number of Berths	Dry	Unit	Dry	Unit	Dry	Unit
Jeddah	13	14000	4500	150000	65000	65000	65000
Jubail	4	9000	4500	10000	10000	6000	6000
Ad Dammam	13	14000	4500	150000	65000	65000	65000
Dubai	12	9000	6500	39000	39000	3000	24000
Yanbu	4	9000	4500	10000	10000	6000	6000

Table 3-1 SPOD data requirements

SPOD data requirements for optimization. SPODs listed comprise all those found in JTOTPFDDL used during testing of the model. The offload rate refers to the amount of cargo (STONS/day) that can be transferred off ships at berths specifically designated for military operations. The storage capacity refers the amount of space available to store cargo while it awaits transport out of the SPOD. The road/rail capacity refers to the capacity of the road and rail networks out of the SPOD. The data for each SPOD is derived from World Port Summaries that are compiled by Military Traffic Management Command Transportation Engineering Agency (MTMC TEA) [MTMC-1999].

	BSR	SC
JTOTPFDDL Requirements	236	236
Reassignment Heuristic Results	235/236	201/236

Table 3-2 Reassignment Heuristic Results (base case)

Base case results. The reassignment heuristic berths 99% of the ships while changing SPOD assignment only 85%.

To test the reassignment with SPOD throughput disruptions, a set of random SPOD disruptions is used to alter the original capabilities of the SPODs listed in

JTOTPFDDL. Each disruption reduces one or more of the SPOD capabilities by various fractions. Once a disruption occurs, the SPOD "restores" itself at a rate of 25% a day.

Table 3-3 displays a portion of the list used to test the reassignment heuristic with periodic SPOD throughput disruptions. Even though many of the SPODs listed in JTOTPFDDL have individual capacities sufficient to support the entire JTOTPFDDL plan, the number and severity of the disruptions significantly alters the ships' optimal schedules. Each SPOD typically encounters 50 disruptions of one sort or another over the 100-day time horizon. The disruptions range from a minor reduction of a single capability at a SPOD to the elimination of a SPOD.

SPOD	Period	Event	Efficiency Rates of Each Capability Area		
			% Offload Rate	% Storage Capacity	% Road/Rail Capacity
Ad Damman	1	No	100	100	100
Ad Damman	2	Yes	25	25	0
Ad Damman	3	Yes	50	50	18.7
Ad Damman	4	No	75	75	43.7
Ad Damman	5	Yes	100	100	51.5
Ad Damman	6	No	100	100	76.5
Ad Damman	7	No	100	100	100
Ad Damman	8	No	100	100	100
Ad Damman	9	Yes	25	25	0
Ad Damman	10	Yes	50	50	18.7

Table 3-3 SPOD disruptions

List of disruptions at Ad Damman during the first 10 time periods. Bold faced numbers indicate the particular capability reduced during each disruption. E.g., On day 2, Ad Damman's offload rate is reduced to 25%, storage capacity is reduced to 25% and Road and Rail capacity is reduced to 0%.

Table 3-4 shows the results of the reassignment heuristic with SPOD throughput disruptions. Despite a significant number of disruptions, the reassignment heuristic berths 99% of the ships, but schedules less than 50% of the ships to berth at their originally designated SPOD. This is a significant degradation from the base case.

	BSR	SC
JTOTPFDDL Requirements	236	236
Heuristic Disrupted Results	234/236	88/236

Table 3-4 Reassignment Heuristic Results (disruption case)

Disruption case results. The reassignment heuristic berths 99% of the ships, but the number of SPOD changes significantly increases from the base case (15% to 65% of the time).

To objectively assess the quality of the SPOD reassignment heuristic, or that of any suggested embellishment or improvement of the heuristic, we present an equivalent mathematical optimization model.

1. Ship-to-SPOD Reassignment Optimization

The following mathematical formulation provides a means for optimally re-routing notional ships while taking into account many of the considerations used by logisticians during a conflict. Although we do not anticipate that such an optimization will be incorporated into a simulation, for completeness, the discussion assumes that this will be the case.

a. Formulation Discussion

The Ship-to-SPOD Reassignment Optimization, referred to herein as “the optimization”; minimizes the deviance from the original TPFDDL scheduled arrival dates and SPODs and imposes penalties for failing to meet the CINC’s required dates. It also attempts to re-route items that have a higher priority more efficiently by imposing higher penalties for deviations from the original plan for those high-priority units than for lower-priority units. The optimization considers port capacity, in-theater logistics network capacity, ship to port distances, and ship size and composition as constraints. Additionally, the number of integer variables ($BERTH_{s,p,t}$) is restricted throughout the

optimization as a means of reducing the compilation and computation time as much as possible.

Optimized solutions are determined at the end of each time period, i.e., day, as would be the case if the optimization were incorporated into a simulation. It produces a ship-to-SPOD schedule for all ships that have not been scheduled to berth during previous days of the simulation ($atsea_s=1$). The time horizon for the optimization (TH) is the set of all time periods listed in the TPFDDL. Any scheduling solutions are limited to the current planning horizon. The current planning horizon is from the present time period (td) to the end of the time horizon ($t = td, td+1 \dots TH$).

Because ships that arrived during previous days of the simulation may still occupy berths, the optimization counts a berth as occupied for all time periods from the date a ship arrives (tb) to the date it is scheduled to depart ($tb+ult$, ult refers to the number of time periods required to unload the ship). Similarly, because cargo surpluses incurred during previous days of the simulation may still occupy storage space at each SPOD, the optimization calculates excess cargo ($HOLDATSPOD_{p,m,td-1}$) prior to determining a new schedule.

b. Dimensions and Indices

$s \in S$	ship {notional ships described earlier}
$c \in C$	cargo {TPFDDL record, e.g., ULN001, NURR002 }
c_s	cargo on ship s
$m \in M$	materiel {logistically similar items, e.g., unit, sustainment dry, sustainment POL}
m_c	materiel type of cargo c
$a \in A$	assembly area {e.g., a001, a002}
a_c	assembly area of cargo c
$t \in TH$	time period (TH is an ordinal index, e.g., 1,2,...,~100 days)
$tr \in TH$	time period of a required delivery date

tr_c	time period required for delivery of cargo c
$td \in TH$	first planning period in current planning horizon
$t \in T$	planning period $T \equiv \{td, td+1, \dots, \ TH\ \}$
$tb \in TH$	berth period, during which unloading begins
$p \in P$	port of debarkation (SPOD, e.g., Jeddah, Ad Damman, ...)
$l \in L$	lag periods {e.g., -5(early), -4, ..., 0(delivery on time), +4, +5(late)}
$\underline{t}_{s,p}, \bar{t}_{s,p} \in T$	earliest, latest planning period for ship s to arrive at SPOD p
Note that planning period $\underline{t}_{s,p} \geq td$.	

c. Units Description

penalty	objective function units
stons	cargo weight in short tons
berths	ship unloading positions at an SPOD
period	time unit (uniform duration)

d. Data

$atsea_s$	<i>true</i> if ship s is not yet berthed during planing period td <i>false</i> otherwise
$pplan_s$	planned SPOD for ship s , $pplan_s=0$ for all ships not previously assigned a SPOD
$tplan_s$	planned arrival period for ship s
$stons_{s,m}$	weight carried by ship s of materiel m (stons)
pri_c	priority of cargo c (penalty/penalty)
$berths_p$	berths in SPOD p (berths)
$offloadrate_{p,m}$	rate at which SPOD p can unload materiel m from each ship berthed (stons/period)
$maxmove_{p,m}$	rate at which SPOD p can start moving materiel m toward assembly areas (stons/period)
$maxhold_{p,m}$	SPOD p local storage capacity for materiel m (stons)
$movetime_{p,a}$	time to move cargo from SPOD p to assembly area a (periods)
$pval_t$	present value of costs incurred in planning period t (present cost/future cost) (e.g., $\equiv e^{-fog \cdot t}$, with $fog \cong 5\%/100\%$ per period into future)
$maxholdstat_{p,m,t}$	proportion of the original rate at which SPOD p can start moving materiel m toward assembly areas during period t
$offloadstat_{p,m,t}$	proportion of the original rate at which SPOD p can unload materiel m from each ship berthed during period t

$maxholdstat_{p,m,t}$ proportion of the original local storage capacity at SPOD p for materiel m during period t

e. Persistence Data and Penalties

$ontimepen_l$	penalty for delivery lag from $trdd$ of l periods (penalty)
$berthpen$	penalty for each ship with no planned berth (penalty/berth)
$backlogpen$	penalty for movement delays at SPOD (penalty/period)
$excesspen$	penalty for exceeding $maxhold_{p,m}$ (penalty/ston)
$spodpen$	penalty for rescheduling a future plan for ship s to berth at a new SPOD $p \neq pplan_s$ (penalty)
$tberthpen$	penalty for rescheduling a future plan for ship s to berth during a planning period $t \neq tplan_s$ (penalty/period)
$persistpen$	penalty for each change of any kind to the future plan
$difspodpen$	penalty for rescheduling a ship s to berth at SPOD p different from SPOD originally designated in the TPFDDL

f. Derived Data

$stmin_s, stmax_s$ earliest, latest period that ship s can berth anywhere,

$$\text{e.g., } stmin_s \equiv \min_p (t_{s,p}), \quad stmax_s \equiv \max_p (\bar{t}_{s,p})$$

$$ult_{s,p} \quad \text{unloading time of ship } s \text{ at SPOD } p \text{ (periods)}$$

$$\equiv \lceil \max_m \{ stons_{s,m} / offloadrate_{p,m} offloadstat_{p,m,t} \} \rceil$$

$$urr_{s,m,p} \quad \text{uniform unloading rate of ship } s, \text{ materiel } m, \text{ at SPOD } p$$

$$(\text{stons/period}) \equiv stons_{s,m} / ult_{s,p}$$

g. Variables

$BERTH_{s,p,tb}$	=1 if ship s plans to berth at SPOD p at start of planning period tb and to commence unloading during t , =0 otherwise (berth, binary)
$NOBERTH_s$	=1 if ship s has no planned berth (berth, continuous)
$HOLDATSPOD_{p,m,t}$	materiel m held at SPOD p at end of planning period t (stons) $HOLDATSPOD_{p,m,t=1}$ is the initial state at the SPOD.

$EXATSPOD_{p,m,t}$ excess materiel m held at SPOD p at end of planning period t
 $\equiv \max(HOLDATSPOD_{p,m,t} - maxhold_{p,m}, 0)$ (stons)
 $SPOD2FLOT_{p,m,t}$ materiel m moved out of SPOD p during planning period t
(stons)

h. Formulation

Min

$$\sum_{\substack{s|atsea_s=true \\ \&td \geq stmin_s}} \sum_{c_s} \sum_{m_c} \sum_p \sum_{\substack{tb=\max(t_{s,p},td) \\ |maxmove_{p,m} > 0}}^{\bar{t}_{s,p}} pval_{tb} pri_c ontimepen_{tb+ult_{s,p}-1+movetime_{p,a(c)}-tr_c} BERTH_{s,p,tb} \quad (1.1)$$

$$+berthpen \sum_s NOBERTH_s \quad (1.2)$$

$$+backlogpen \sum_{\substack{p,m,t \\ |t \geq td \\ \&maxmove_{p,m} > 0}} (pval_t / maxmove_{p,m}) HOLDATSPOD_{p,m,t} \quad (1.3)$$

$$+excesspen \sum_{\substack{p,m,t \\ |t \geq td}} pval_t EXATSPOD_{p,m,t} \quad (1.4)$$

$$+spodpen \sum_{\substack{s|atsea_s=true \\ \&pplan_s \neq 0}} \sum_{p|p \neq pplan_s} \sum_{tb=\max(t_{s,p},td)}^{\bar{t}_{s,p}} pval_{tb} BERTH_{s,p,tb} \quad (1.5)$$

$$+tberthpen \left(\sum_{\substack{s|atsea_s=true \\ \&pplan_s \neq 0}} \sum_{p|p \neq pplan_s} \sum_{tb=\max(t_{s,p},td)}^{\min(\bar{t}_{s,p}, tplan_s-1)} pval_{tb} (tplan_s - tb) BERTH_{s,p,tb} \right. \\ \left. + \sum_{\substack{s|atsea_s=true \\ \&pplan_s \neq 0}} \sum_{p|p \neq pplan_s} \sum_{tb=\max(t_{s,p}, tplan_s+1, td)}^{\bar{t}_{s,p}} pval_{tb} (tb - tplan_s) BERTH_{s,p,tb} \right) \quad (1.6)$$

$$\begin{aligned}
& + persistpen \times \\
& \left(\sum_{\substack{s|atsea_s=true \\ \& pplan_s \neq 0}} pval_{tplan_s} (1 - BERTH_{s,pplan_s,tplan_s}) \right. \\
& \left. + \sum_{\substack{s|atsea_s=true \\ \& pplan_s \neq 0}} \sum_{p|p \neq pplan_s} \sum_{\substack{tb=\max(\underline{t}_s,p,td) \\ |tb \neq tplan_s}}^{\bar{t}_{s,p}} pval_{tb} BERTH_{s,p,tb} \right) \quad (1.7)
\end{aligned}$$

$$+ difspodpen. \sum_{s|atsea_s=true} \sum_p \sum_{t \geq td} BERTH_{s,p,t} origspod_{s,p} \quad (1.8)$$

Subject to:

$$\sum_p \sum_{tb=\max(\underline{t}_s,p,td)}^{\bar{t}_{s,p}} BERTH_{s,p,tb} + NOBERTH_s = 1 \quad \forall s | atsea_s = true \quad (2)$$

$$\begin{aligned}
& \sum_{\substack{s|atsea_s=true \\ \& t \leq \bar{t}_{s,p} - ult_{s,p} + 1 \\ \& t \geq \underline{t}_{s,p}}} \sum_{tb=\max(t-ult_{s,p}+1,td)}^t BERTH_{s,p,tb} \leq berths_p - \sum_{\substack{s|atsea_s=false \\ \& pplan_s=p \\ \& t \leq tplan_s + ult_{s,p} - 1 \\ \& t > tplan_s}} 1 \\
& \forall p, t | t \geq td \quad (3)
\end{aligned}$$

$$\begin{aligned}
& HOLDATSPOD_{p,"unit",t-1} + \sum_{\substack{s|atsea_s=false \\ \& pplan_s=p \\ \& t=tplan_s+ult_{s,p}-1}} stons_{s,"unit"} \\
& + \sum_{\substack{s|atsea_s=true \\ \& t \leq stmax_s+ult_{s,p}-1 \\ \& t \geq stmin_s+ult_{s,p}-1 \\ \& stons_{s,"unit"} > 0}} stons_{s,"unit"} BERTH_{s,p,t-ult_{s,p}+1}
\end{aligned}$$

$$= SPOD2FLOT_{p, "unit", t} + HOLDATSPOD_{p, "unit", t} \quad \forall p, t | t \geq td \quad (4)$$

$$\begin{aligned} & HOLDATSPOD_{p, m, t-1} + \sum_{\substack{s | atsea_s = false \\ \& pplan_s = p \\ \& t \leq tplan_s + ult_{s, p} - 1 \\ \& t > tplan_s}} urr_{s, m, p} \\ & + \sum_{\substack{s | atsea_s = true \\ \& t \leq stmax_s + ult_{s, p} - 1 \\ \& t \geq stmin_s}} \sum_{\substack{tb = \max(t_{s, p}, t - ult_{s, p} + 1, td) \\ \min(\bar{t}_{s, p}, t)}} urr_{s, m, p} BERTH_{s, p, tb} \\ & = SPOD2FLOT_{p, m, t} + HOLDATSPOD_{p, m, t} \quad \forall m \neq "unit", p, t | t \geq td \quad (5) \end{aligned}$$

$$HOLDATSPOD_{p, m, t} \leq maxhold_{p, m} maxholdstat_{p, m, t} + EXATSPOD_{p, m, t} \quad \forall p, m, t \geq td \quad (6)$$

$$BERTH_{s, p, tb} \in \{0, 1\} \quad \forall s, p, t_{s, p} \leq tb \leq \bar{t}_{s, p} \quad (7)$$

$$NOBERTH_s \geq 0 \quad \forall s \quad (8)$$

$$HOLDATSPOD_{p, m, t} \geq 0 \quad \forall p, m, t \quad (9)$$

$$EXATSPOD_{p, m, t} \geq 0 \quad \forall p, m, t \quad (10)$$

$$maxmove_{p, m} maxmovestat_{p, m, t} \geq SPOD2FLOT_{p, m, t} \geq 0 \quad \forall p, m, t \quad (11)$$

i. Verbal Formulation

The objective function expresses the total present value of penalties (or rewards) for:

- (1.1) assuming immediate shipment from berth SPOD, prioritized early or late penalty (or reward) at destination assembly area;
- (1.2) failing to find berths for ships;
- (1.3) backlog days at the SPOD awaiting shipment to assembly areas;
- (1.4) excess materiel held at the SPOD;
- (1.5) rescheduling destination SPOD from a prior plan;
- (1.6) rescheduling berth dates from a prior plan;
- (1.7) rescheduling anything at all; and
- (1.8) rescheduling destination SPOD different from the ship's SPOD designated by the original TPFDDL.

Constraints:

- (2) Each ship still at sea berths at most once during the remaining planning horizon. Because the optimization does not require any ship at sea to berth during any planning horizon, there is always a feasible berth plan (i.e., an admissible mixed integer solution exists) for the initial planning horizon. During any subsequent planning horizons when prior ship berthing and materiel states are fixed exogenous conditions, there is always a feasible berth plan. That is, prior conditions for any planning horizon can be diagnosed for inconsistencies such that existence of a conditioned integer solution is still guaranteed.
- (3) Constraints ensure that the berth capacity of each SPOD is honored during each planning period, where berths may be still be occupied by ships that have arrived earlier, but that are still unloading.
- (4) Constraints balance the flow of "unit" cargo through each SPOD. Each "unit" cargo joins the SPOD logistics system only when it has been completely offloaded. The constraint ensures that, at each SPOD, the total amount of "unit" cargo unloaded during previous periods but not yet transported out of the SPOD plus the amount of "unit" cargo unloaded from ships berthed during previous periods but still unloading plus the amount of "unit" cargo unloaded from ships berthed during the current period must equal the amount of "unit" cargo transported out of the SPOD during the current period plus any "unit" cargo remaining to be transferred in subsequent periods.
- (5) Constraints balance the flow of "non-unit" cargo through each SPOD. "Non-unit" materials are unloaded uniformly and continuously. The constraint ensures that, at each SPOD, the total amount of "non-unit" cargo unloaded during previous periods but not yet transported out of the SPOD plus the amount of "non-unit" cargo unloaded from ships berthed during previous periods but still unloading plus the amount of "non-unit" cargo unloaded from ships berthed during the current period must equal the amount of "non-unit" cargo transported out of the SPOD during the current period plus any "non-unit" cargo remaining to be transferred in subsequent periods.
- (6) Constraints compute any excess materiel held at a SPOD. Any such excesses are penalized by the objective function (1.3).

Constraints (7) require binary berthing decisions, (8) require that the indication of each ship without a planned berth is nonnegative, while (9) - (10) require nonnegative materiel storage and excess storage, and (11) require nonnegative materiel flows from SPOD to assembly areas, with a simple upper bound each such flow.

2. Data

a. Ship Arrival Time Window at SPOD Calculation

In addition to creating a list of notional ships and assigning all of the applicable records from the TPFDDL to these ships, other calculations are necessary prior to any re-routes by the optimization. Of particular importance are the arrival time windows for each notional ship at each port not assigned in the original TPFDDL but available in theater. In order for the optimization to constrain ship arrival times at each SPOD to reflect time and/or distance constraints associated with SPOE-to-SPOD transit times and availability requirements at pre-designated assembly areas for units and supplies delineated in the TPFDDL, each notional ship's arrival window at any particular SPOD is limited.

Figure 3-1 outlines the considerations associated with the calculation of the arrival time windows for each ship. The SPODs shown are consistent with those encountered in the JTOTPFDDL. The arrival time window for each notional ship at each of the SPODs in theater is calculated by following steps:

1. Determine a Go Point. A Go Point is a location that each ship is assumed to pass through while enroute to each SPOD port.
2. Determine the distance from each SPOD p located in the TPFDDL to the Go Point (SPODtoGPT_p). The distance units are days and based on a ship's transit speed of 15 knots.
3. Determine the distance from each SPOD p to all of the other SPODs in theater (SPODtoSPOD_{pp}). The distance units are days and based on a daily travel distance over land of 450 miles.

4. Establish an arrival date for each notional ship s at the Go Point (DATEatGPT_s). This is determined by subtracting the distance in days to the Go Point from the ship's original SPOD ($\text{SPODtoGPT}_{\text{origp}}$) from the date of the ship's original EAD

($\text{EAD}_{s,\text{origp}}$) :

$$\text{DATEatGPT}_s = \text{EAD}_{s,\text{origp}} - \text{SPODtoGPT}_{\text{origp}}.$$

5. Determine the beginning of the arrival window for each notional ship s for each SPOD p in theater (SPODEAD_{sp}). This is calculated by adding the distance from each SPOD p to the Go Point (SPODtoGPT_p) to the date that each ship arrives at the Go Point (DATEatGPT_s):

$$\text{SPODEAD}_{sp} = \text{DATEatGPT}_s + \text{SPODtoGPT}_p.$$

6. Determine the end of the arrival window for each notional ship s for each SPOD p in theater (SPODLAD_{sp}). This is calculated by adding the distance from each SPOD p to the ship s 's original SPOD

($\text{SPODtoSPOD}_{\text{porigp}}$) to the ship's original LAD ($\text{LAD}_{s,\text{origp}}$):

$$\text{SPODLAD}_{sp} = \text{LAD}_{s,\text{origp}} + \text{SPODtoSPOD}_{\text{porigp}}$$

Arabian Peninsula and Vicinity

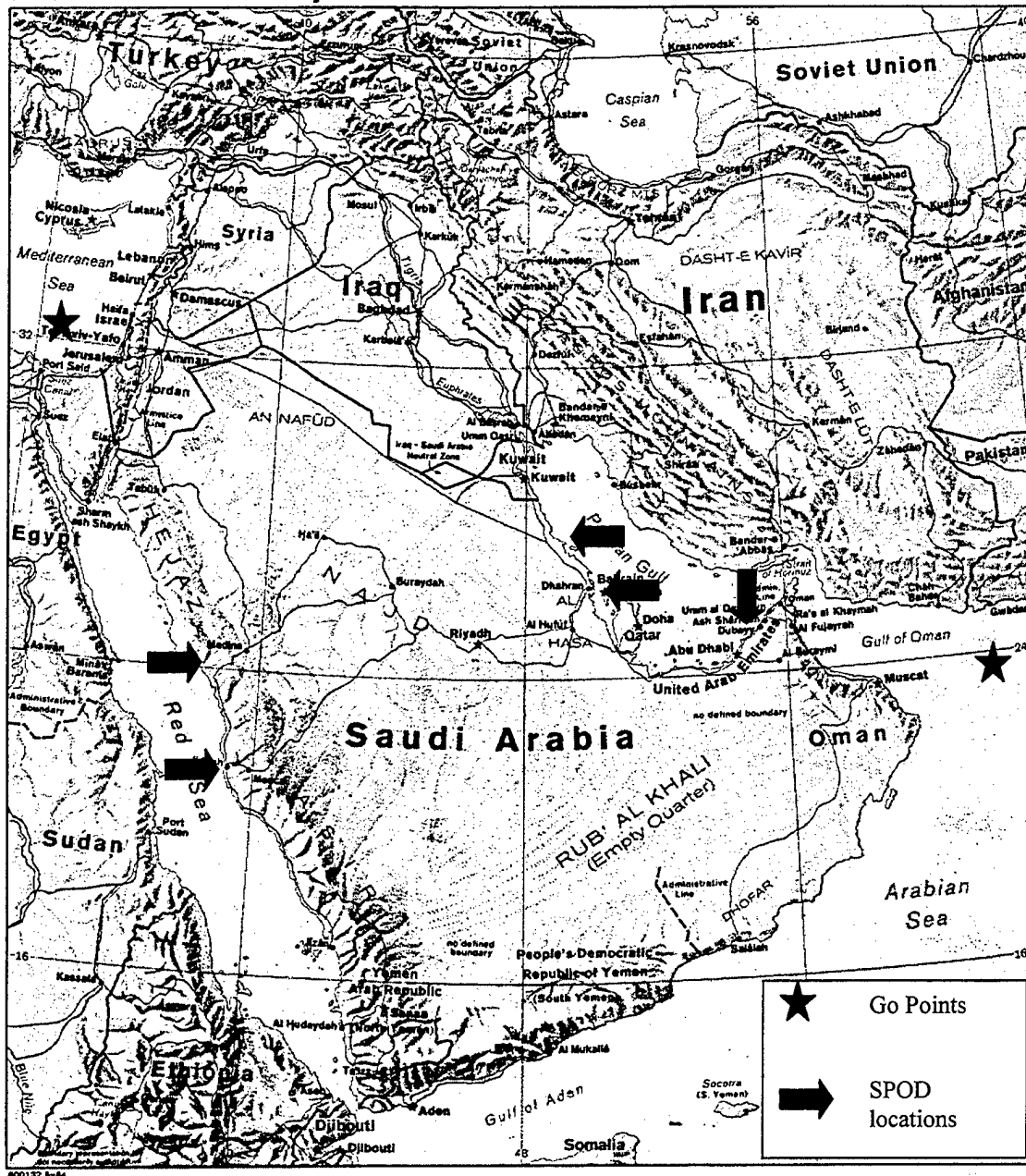


Figure 3-1 Go Point Discussion

Ships enroute from SPOEs in Europe and the East Coast of the U.S. have to pass through the Go Point located in the Mediterranean Sea to reach all of the SPODs in this theater. Ships enroute from SPOEs on the West Coast of the U.S. have to pass through the Go point located in the Indian Ocean. Each of these go points provides a common datum from which to calculate distances and therefore arrival dates for each ship at each SPOD in theater. Map from [Univ. Texas 1999].

This procedure ensures notional ships cannot arrive at any SPOD in theater earlier than would be physically possible during an actual transit. The procedure

also ensures that units and supplies have enough transit time to arrive at a pre-designated assembly point if the ship carrying them is rerouted to a different SPOD.

In the Southwest Asia scenario shown in Figure 3-1, the distance between some ports is quite significant. JTOTPFDDL lists 5 SPODs available to U.S. forces, 2 on the Red Sea and 3 on the Persian Gulf. A ship that originates from the U.S. East Coast requires a different go point than a ship originating from the U.S. West Coast. In scenarios involving smaller theaters such as a Balkan conflict where most ports are relatively close, a single Go Point might be used.

b. SPOD Data

SPOD throughput can be described in a variety of ways using many different characteristics. For the purpose of this model, SPOD throughput characteristics are aggregated into three areas:

- Offload Rate ($offloadrate_{p,m}$): The amount of cargo (STONS/day) that can be transferred off ships at berths specifically designated for military operations. The rate is dependent on the type of cargo m (unit, POL, dry) being offloaded.
- Storage Capacity($maxhold_{p,m}$): The amount of space available to store cargo while it awaits transport out of the SPOD. The amount of space is dependent on the type of cargo m e.g. storage tanks for POL, or apron space for unit and dry cargo.
- Transportation network out of SPOD($maxmove_{p,m}$): The capacity of the road and rail networks out of the SPOD by type of cargo m . Approximately 60% of a SPOD's maximum capacity is generally available to military traffic [MTMCTEA 1999]. For planning purposes, the remaining capacity is reserved for commercial traffic, even during combat logistic offloading.

These three limitations determine the amount of time it takes for removing an item of cargo off a ship until that cargo is transported out of the SPOD including any time in

storage. Table 3-1 lists the SPOD's used in JTOTPFDDL and their respective capacities of each area.

Each SPOD is endowed with an efficiency rate ($\max movestat_{p,m,t}$, $offloadstat_{p,m,t}$, and $\max holdstat_{p,m,t}$) that reflects the percentage of the original capacity for each capability area of SPOD p , and each materiel type m at the end of each period t . These efficiency rates can be updated at the end of each period (e.g., by the simulation) to reflect events that impact the capacities of each SPODs.

The number of berths allocated for exclusive military use at each SPOD is required. Table 3-1 lists the number of berths available at the SPODs listed in JTOTPFDDL.

c. Persistence Data

A mathematical programming model that is re-solved after incorporating minor changes to its input data can produce solutions that are dramatically different from the previous optimal solution. In the model, a minor reduction in the capacity of a single SPOD can result in a significant number of re-routing orders for ships in transit. Many of these updates are superfluous. If a model produces a dramatically revised logistics schedule on a daily basis during actual combat operations, staff logisticians would be inclined to ignore its advice. To maintain a realistic logistical decision-making tool in a simulation, optimization must produce a relatively stable ship schedule over time.

To maintain the integrity of the previous period's schedule, persistence is incorporated into the objective function. "By making a model persistent, a new solution may be obtained that is not too different from the previous solution yet nearly optimal with respect to standard criteria [Brown et al 1997]." In this optimization, a persistence

penalty [see (1.5-1.7) in the objective function] is incurred by any deviation from the previous period's optimal plan, e.g., a change in a ship's arrival date or SPOD. These penalties are large enough to encourage preservation of a stable schedule but are not so large as to inhibit a ship from berthing at all.

3. Incorporating the optimization into a simulation

If the time and resources are available, the optimization can be incorporated into a simulation like WLTAE.

Prior to running a theater-level simulation, several additional setup requirements must be completed to ensure a successful integration of optimization with the simulation.

These requirements include:

- 1) Using SAH, assign all of the lines in the TPFDDL to notional ships objects for later incorporation into the appropriate federation in the simulation. The priority of each ship matches the highest priority ULN assigned to that ship.
- 2) Determine what SPOEs and SPODs are used in the TPFDDL. If SPOEs from both coasts of the United States are used, determine whether one or two go points are necessary based on the geographical location of the SPODs. For each of the SPODs determine the distance over land from all other SPODs. From this information, designate arrival windows for each notional ship at each SPOD in the TPFDDL.
- 3) Determine SPOD capabilities.
- 4) In the optimization, prior to the initial period $td=1$, set the following variable or parameters:
 - a) Specify $HOLDATSPOD_{p,m,0}$ with initial materiel m (if any) at SPOD p ,
 - b) Initialize $atsea_s=true$ for each ship s ,
 - c) Initialize $pplan_s=tplan_s=0$ for each ship s .

Internal to the optimization, subsequent to each planning period td , calling the best incumbent solution from prior planning horizon $tb \geq td$, $BERTH_{s,p,tb}^*$, update the following:

if $BERTH_{s,p,td}^* = 1$,
then,
ship s has berthed at SPOD p at the start of period td , so
 $atsea_s = false$;

if $\exists BERTH_{s,p,tb}^* = 1, tb \geq td$, i.e. if there exists a solution such that ship s is
planning to berth at SPOD p at the start of
period tb ,
then,
set $pplan_s = p$, i.e. the value of the port plan (pplan) for ship s is
equal to the ordinal of the port assigned,
set $tplan_s = tb$, i.e. the value of the time period plan (tplan) for ship
 s is equal to the ordinal of the time period assigned,
and
set $td \leftarrow td + 1$.

Following each period td , the simulation is expected to send an update of the status of each SPODs' capabilities. This update is in the form of a text file that lists the updated efficiency rates ($maxmovestat_{p,m,t}$, $offloadstat_{p,m,t}$, and $maxholdstat_{p,m,t}$) for each SPOD p and materiel type m . The solver determines the best ship schedule based on the current situation at the SPODs and sends any revisions back to the simulation.

4. Optimization Results

This optimization is also implemented in General Algebraic Modeling System (GAMSTTM) and solved by the XA solver [Brook et al 1997] on a 200 MHz processor. XA has been set to terminate when it finds a solution known to have an objective function value within 10% of a truly optimal solution. Table 3-5 summarizes the computation requirements over the 100-day time horizon delineated in JTOTPFDDL.

		Variables		Number of Equations	Solution Times (seconds)
		Discrete	Cont.		
Base Case	Average	40635.88	42804.98	2211.12	54.4615
	Maximum	120699	126336	4416	1547.32
	Minimum	16	309	37	0
Disruption Case	Average	41336.53	44318.35	2216.28	62.3474
	Maximum	120699	126336	4416	985.46
	Minimum	5	314	38	0

Table 3-5 Computational Requirements (Ship-to-SPOD Reassignment Optimization)

Optimization computational requirements of the 2 cases tested over all 100 days of the JTOTPFDDL scenario.

As with the reassignment heuristic, the optimization is tested using inputs from JTOTPFDDL. For the base case, the capabilities for each of the SPODs are fixed throughout the 100-day planning horizon designated in the TPFDDL and consistent with the data listed in Table 3-1. Table 3-6 compares the results from the model against the requirements delineated in the original TPFDDL.

	BSR	SC	Ave. CPU time
JTOTPFDDL Requirements	236	236	
Optimization Results	236/236	236/236	54.46

Table 3-6 Optimization Results (base case)

Base case results. Optimization schedules all TPFDDL ships to berth at their originally designated SPODs. CPU time is the average time for each solution over the 100 days of the JTOTPFDDL scenario.

The optimization produces a ship-to-SPOD schedule that meets the intent of the original TPFDDL. The optimization schedules each of the ships to arrive at the SPOD and within the prescribed EAD/LAD window in the TPFDDL.

The optimization is also tested against the same SPOD throughput disruption case as the reassignment heuristic. Figure 3-2 displays the effects of the disruptions on the number of berthings scheduled for each day at Ad Damman. Optimization changes the

base case planned berth date for a ship 70% of the time and SPOD assignment differs from the original SPOD only 30% of the time.

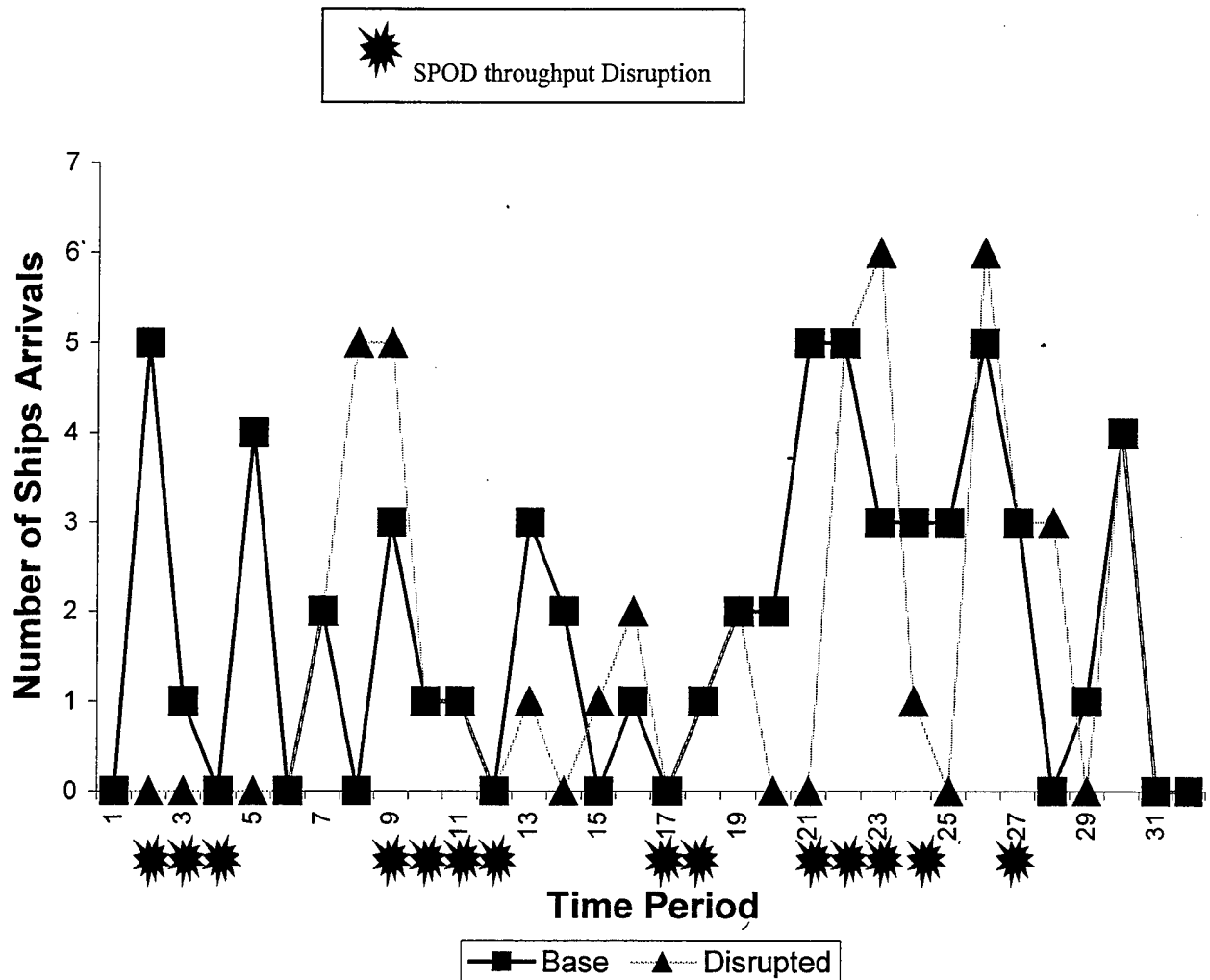


Figure 3-2 Effects of Disruptions on Ship Berths

Comparison of the optimal number of ships berthed at Ad Damman for the base case and for the SPOD throughput disruption simulation during the first 32 days of the time horizon. The disruptions on days 3, 4, and 5 delay arrivals of 10 ships at Ad Damman by a few days. The remaining 2 ships originally scheduled for Ad Damman during the first 10 days in the base case are redirected to alternate SPODs. Similar adjustments are made throughout the entire time horizon.

Table 3-7 shows the results of optimization with SPOD throughput disruptions.

Despite a large number of disruptions over the entire time horizon, optimization is able to

achieve a near 100% BSR. SC drops to 80%, but considering the scope of the disruptions involved, optimization produces a favorable ship-to-SPOD schedule.

	BSR	SC	Ave. CPU time
JTOTPFDDL Requirements	236	236	
Optimization Base Results	236/236	236/236	54.46
Optimization Disrupted Results	235/236	189/236	62.34

Table 3-7 Optimization Results (disruption case)

Comparison of MOEs for the base case and the SPOD throughput disruption simulation. Even after numerous disruptions, the optimization berthed almost all of the ships using a limited number of alternate SPODs. CPU time is the average time for each solution over the 100 days of the JTOTPFDDL scenario.

The optimization tracks existing conditions at each SPOD during a simulation and updates the applicable capability areas as dictated from an exogenous source. Evidently, the optimization can effectively interact with an ongoing simulation like WLTAE.

5. Optimization and Heuristic Comparison

Incorporation of the optimization into a simulation or other logistical planning environment can offer a major improvement over present capabilities. Unfortunately, this improvement has its costs. Optimization software packages are not trivial to incorporate into simulation suites. Formal optimization requires computation time that would delay simulation results. Although optimal solution times for each day of the simulation are generally less than 1 minute, the GAMS generation time for each iteration of the model can take over 10 minutes on a 200 MHz processor. Over the course of a 100-day scenario like JTOTPFDDL, these computation times are significant.

The heuristic has been tested with the same base case and SPOD throughput disruption scenario as the optimization. Table 3-8 compares the results of the heuristic

with those of the paired optimization. The heuristic schedules nearly as many ships to berth as does the optimization. However, the heuristic suggests poorer schedules: more than 50% of the ships are berthed at SPODs that are different than in the original TPFDDL. The heuristic is fast, but the optimization recommends better schedules.

	BSR	SC
JTOTPFDDL Requirements	236	236
Optimization Base Results	236/236	236/236
Heuristic Base Results	235/236	201/236
Optimization Disrupted Results	235/236	189/236
Heuristic Disrupted Results	234/236	88/236

Table 3-8 Optimization and Heuristic Comparison

The heuristic schedules nearly as many ships to berth as optimization, but the quality of the heuristic schedules is worse because more ships are berthed at alternate SPODs.

The reassignment heuristic is not as effective as the formal --- and much more expensive --- optimization. The heuristic reassignments demand more intra-theater transportation, and this is in short supply during a conflict.

Of course, the heuristic can likely be improved, especially with the help of an optimization to suggest where heuristic solutions are flawed and how much better they can be made.

However, even in its current state, we conjecture that the heuristic is good enough, and efficient enough, to incorporate into WLTAE. Despite significant disruptions in many of the SPODs in a theater, the heuristic delivers a majority of the notional ship cargoes, and consequently a majority of the items in the TPFDDL are available in the required time. Delivering the cargo is the overriding goal of any logistical planner.

IV. CONCLUSIONS AND RECOMMENDATIONS

Disruptions to logistical infrastructure should be realistically represented and accommodated throughout a simulation like WLTAE. An automatic decision-making tool is needed within the simulation that can fill the role of logistic planners, rescheduling as necessary to respond to exigent events.

Rescheduling of supplies into a theater to account for changes in SPOD capabilities is accomplished herein in two steps. First, the flows of materiel in the TPFDDL are allocated to notional ships by a ship assignment heuristic. Second, a ship reassignment heuristic reschedules these notional ships to alternate SPODs and/or arrival dates as necessary to respond to disruptions.

The introduction of notional ships into a simulation like WLTAE is a significant improvement over the current practice of representing a stream of unassigned records flowing into an SPOD during each time period of a simulation. These ships realistically represent the logistics posture of the theater, and permit rescheduling of the flow of material in a fashion more in keeping with real-life logistics planning.

The ship assignment heuristic provides a cargo mix that nearly minimizes the number of notional ships.

The Ship-to-SPOD Reassignment heuristic is fast and cheap, but not as effective as formal optimization. The heuristic can produce adequate schedules that deliver a majority of the items in the TPFDDL into a theater in the required time, notwithstanding significant disruptions in many of the SPODs in a theater. Delivering the cargo is the overriding goal of any logistical planner.

The optimization used to measure the effectiveness of the Ship-to-SPOD Reassignment heuristic can be incorporated into a simulation like WLTAE as well (computational resources permitting). Additionally, the optimization can provide a benchmark to measure the effectiveness of the Ship-to-SPOD Reassignment heuristic and any other potential berth scheduling heuristics.

Further research for a better heuristic as an alternative to the Ship-to-SPOD Reassignment heuristic is highly recommended.

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